Mach Cutoff Analysis and Results from NASA's Farfield Investigation of No-boom Thresholds

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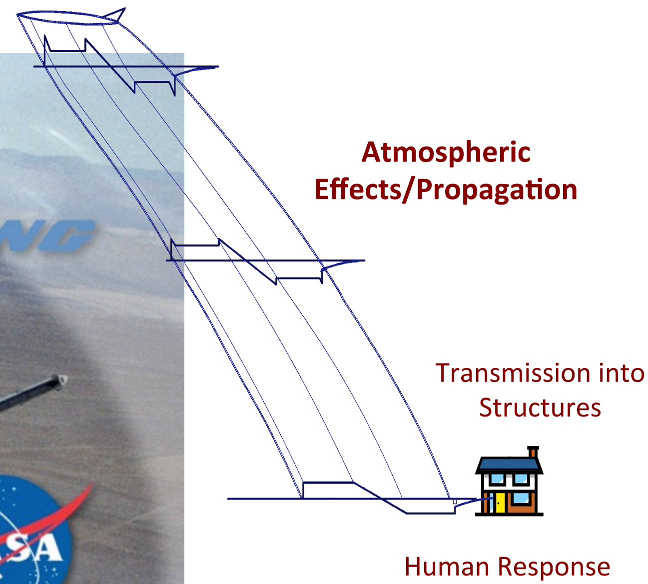
NASA Armstrong Flight Research Center

FARFIELD INVESTIGATION OF NO-BOOM THRESHOLDS (FAINT)



Aeronautics Flight Research

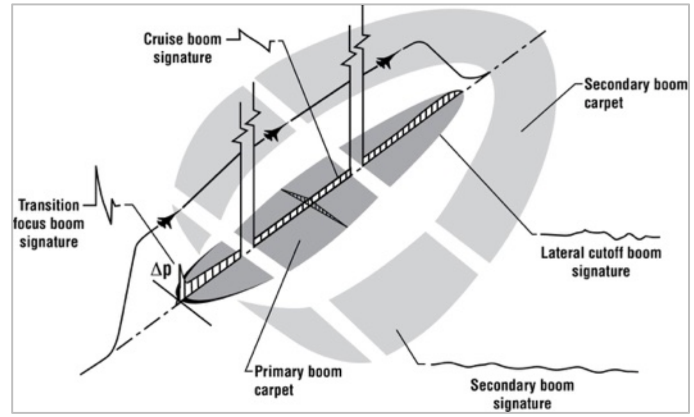
- Over 60 years of flight research (NACA Muroc Flight Test Unit)
- Edwards Air Force Base (EAFB)
- Remote Location
- 350 Testable Days Per Year
- Extensive Range Airspace
- Supersonic Corridor

Topics of Discussion

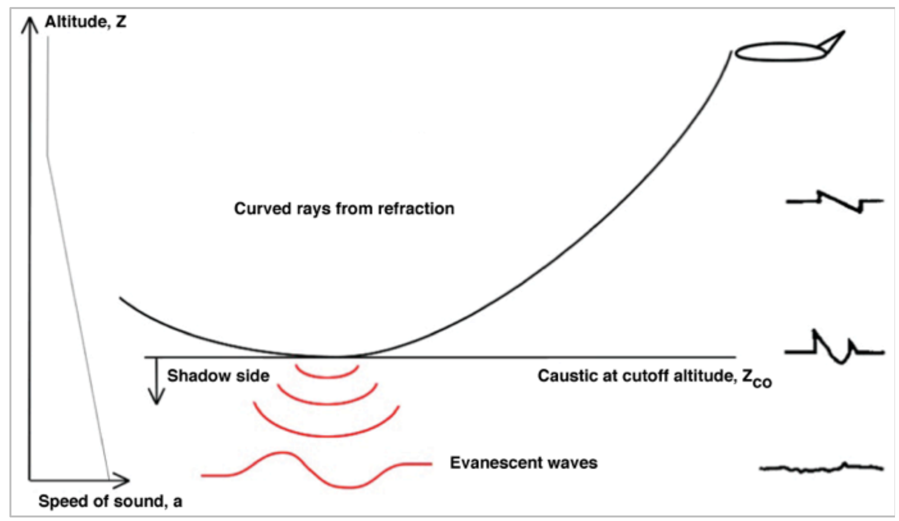
- Motivation & Objectives
- Test Setup
- Flight Profile Planning
- Analysis
  - Mach cutoff calculations
  - Metrics for Mach cutoff acoustics
  - Noise levels due to Mach cutoff
  - Sensitivity Analysis
- Summary & Considerations

MOTIVATION & BACKGROUND

- **What is Mach Cutoff flight?**
  – Supersonic flight when sonic boom rays do not reach the ground

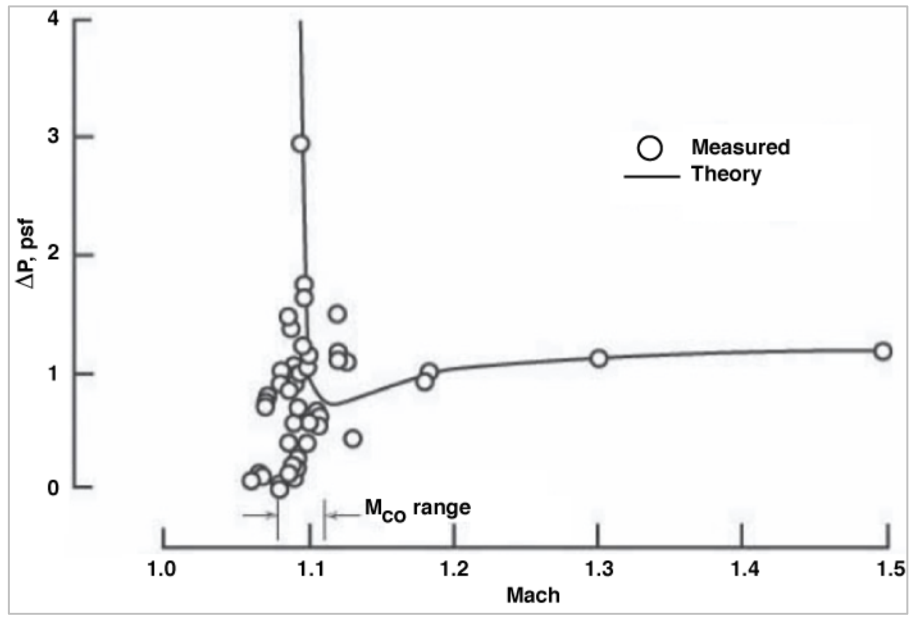


  – Rays refract due mostly to temperature gradient
- Commercial implications
  – "Boomless" flight
  – Speeds up to Mach 1.3
  – Increase in operations by over 30%



MOTIVATION & BACKGROUND, *CONT.*

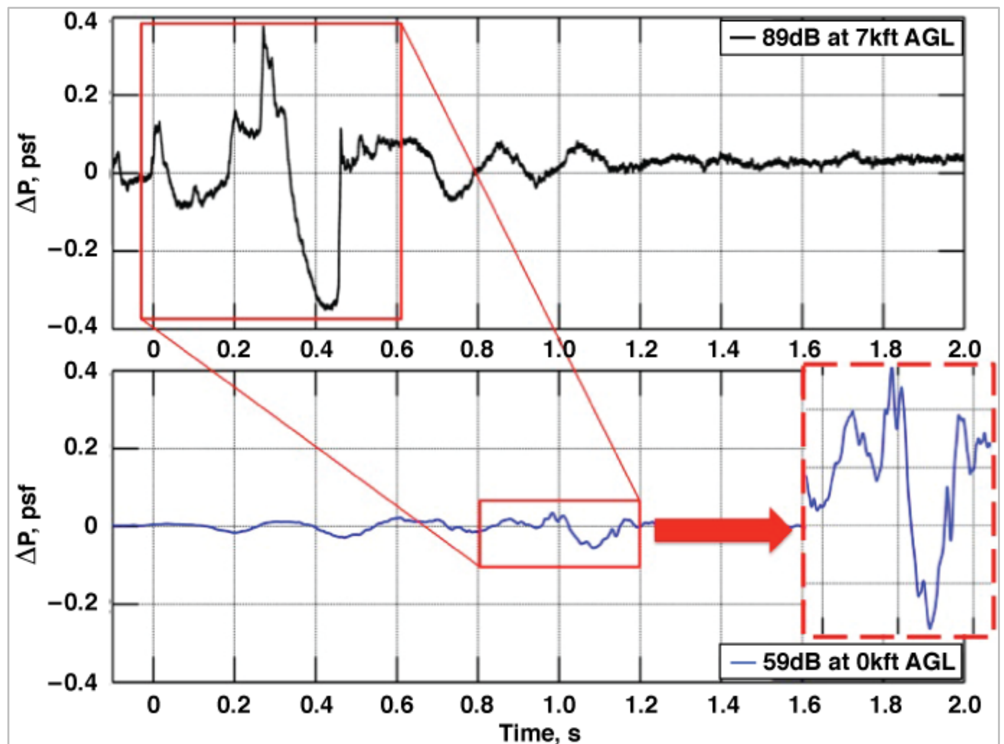
- **Need: Understanding of entire sonic boom envelope**
- Change in ICAO/FAA regulations
- Notable noise due to Mach cutoff flight (M_{CO})
- Inconclusive results from previous tests
- Limitations to common numerical predictions:
  - Based on geometrical acoustics
  - No solutions in shadow zones



Results from 1970 Bare Reactor Experiment, Nevada (BREN) study

Primary Objectives

- Study evanescent wave field
  - Finely spaced measurements
  - Attenuation and increase in signature length
  - Evanescent decay in shadow zone
- Design tools for flight planning and post-flight analysis
- Develop noise–M_{CO} relationship
- Build database



Flight Profile Planning

- Goal: Produce a range of cutoff altitudes (Z_{CO}) between 2500 – 8000 ft *(762.0 – 2438.4 m)*
  - Assume initial flight altitude (Z) and heading
  - Calculate required Mach (M)
- Rays refract above ground when their propagation speed (V_P) exceeds the airplane ground speed (V_G):

$$V_P / V_G \geq 1.0$$

where

$$V_G = Ma_0 - u_{n_0} \quad (1)$$

$$V_P = \{a(Z) - u_n(Z)\} \quad (2)$$

a : speed of sound
u_n : wind speed direction of propagation
0 : subscript denotes at flight altitude

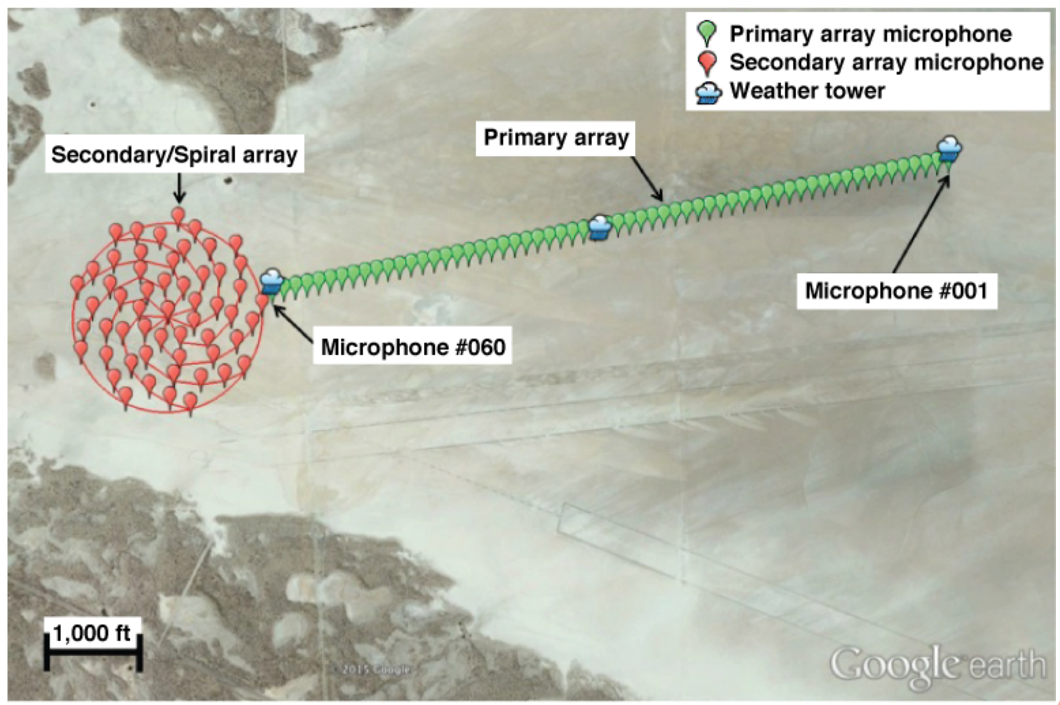
- Because V_P increases toward the ground:

$$Z_{CO} = Z \ @ \ \max\{V_P \geq V_G\} \quad (3)$$

- Use Eq. 1 to compute M that satisfies Eq. 3

TEST SETUP

- Flight Conditions
  - F-18B airplane
  - Mach 1.128 – 1.174 and 34400 – 39300 ft *(10.5 – 12.0 km)* pressure altitude
- 7375 ft *(2.2 km)*, 125 ft *(38 m)* spaced linear microphone array at 2300 ft *(0.7 km)* mean sea level
  - 60 microphones
- PCBoom[1] used for initial flight planning

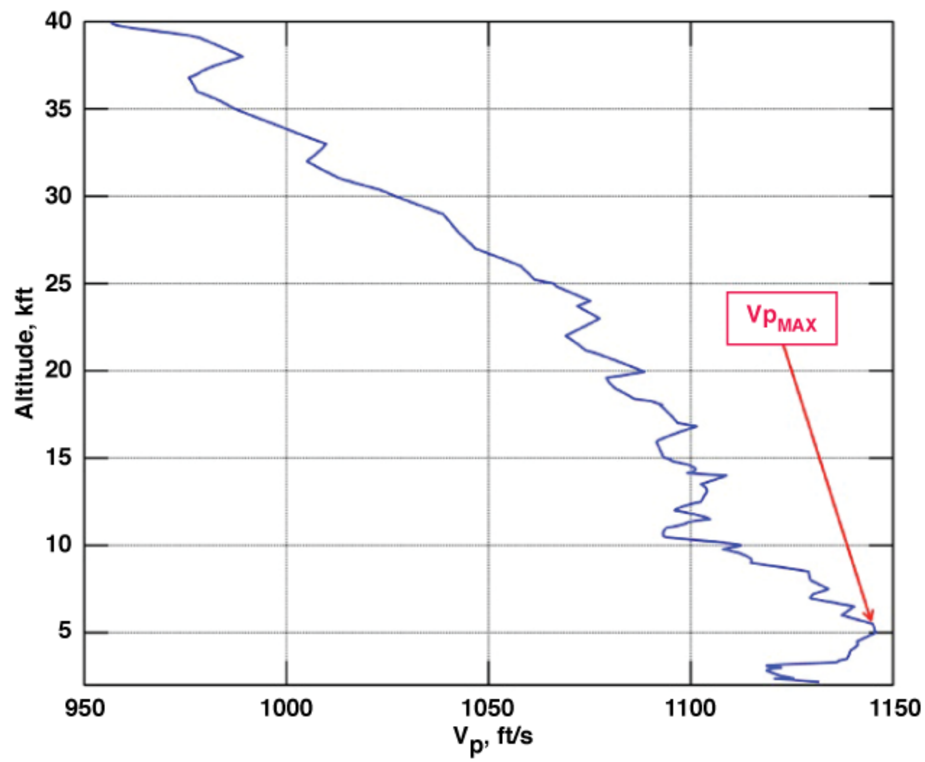


[1] PCBoom was developed by Wyle (El Segundo, California)

MACH CUTOFF CALCULATIONS

- Mach threshold (M_T): Fastest Mach for M_{CO}
- M_T is independent of Z_{CO}
- Dependent only on atmospheric conditions, mostly $V_{P,max}$

$$M_T = \frac{1}{a_0}\left[V_{P_{MAX}} + u_{n_0}\right]$$



METRICS FOR MACH CUTOFF ACOUSTICS

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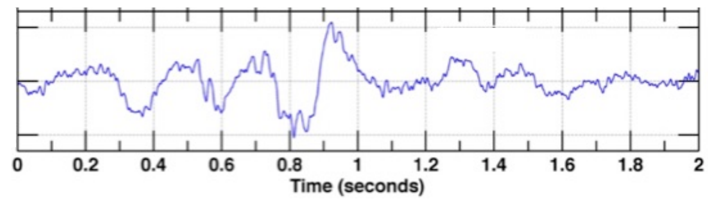
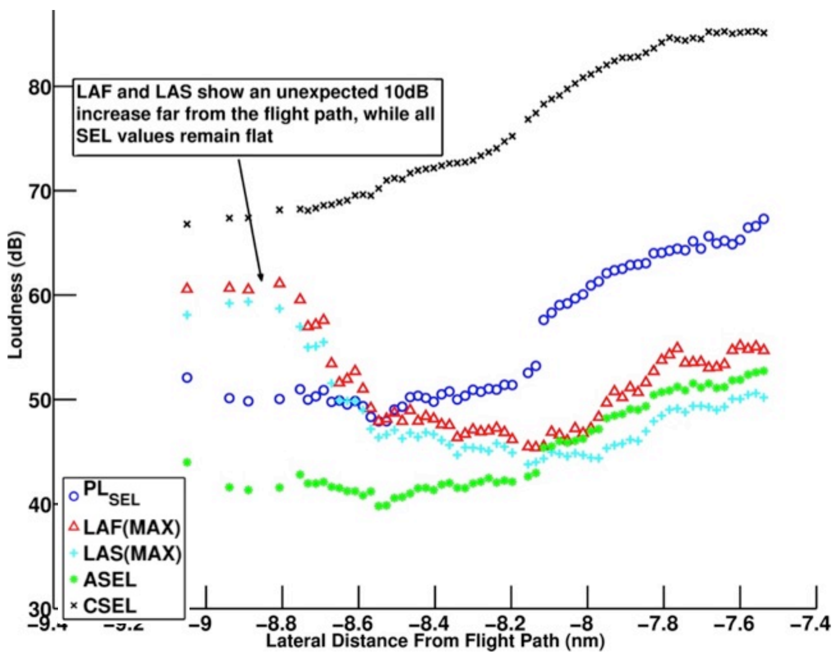
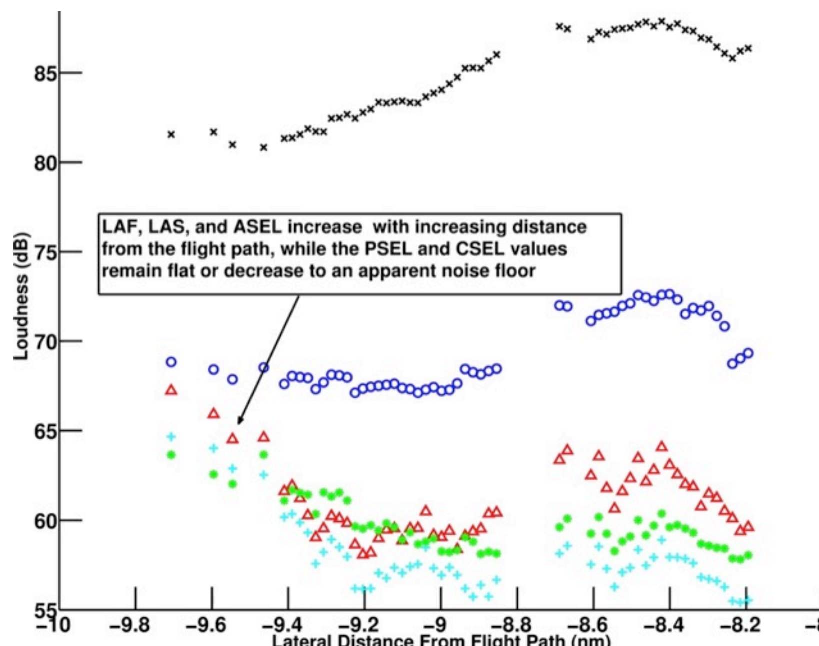


- Overpressure alone not sufficient for sonic boom analysis
- Familiar metrics less applicable for waveforms near lateral cutoff and beneath Mach cutoff altitude due to variable duration and impulsiveness
- **Perceived Sound Exposure Level (PL_{SEL})**
  - 99% energy windowing
  - Sound Exposure Level (SEL) 1-second normalized integration (ISO 1996)
  - Stevens' Mark VII Perceived Level weighting





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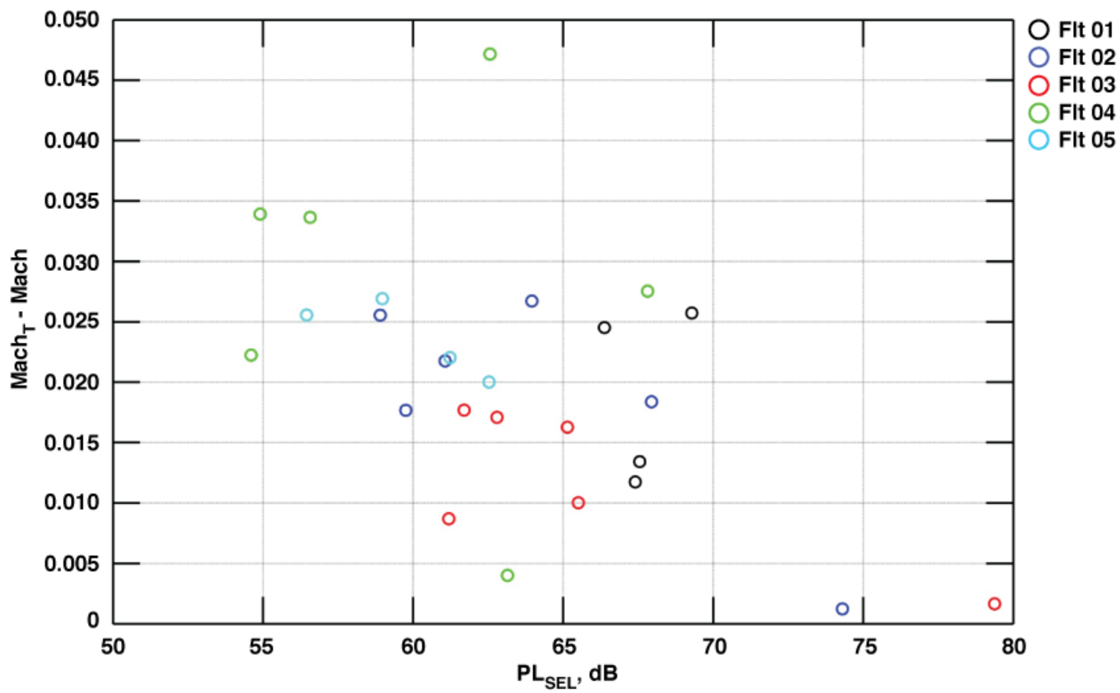
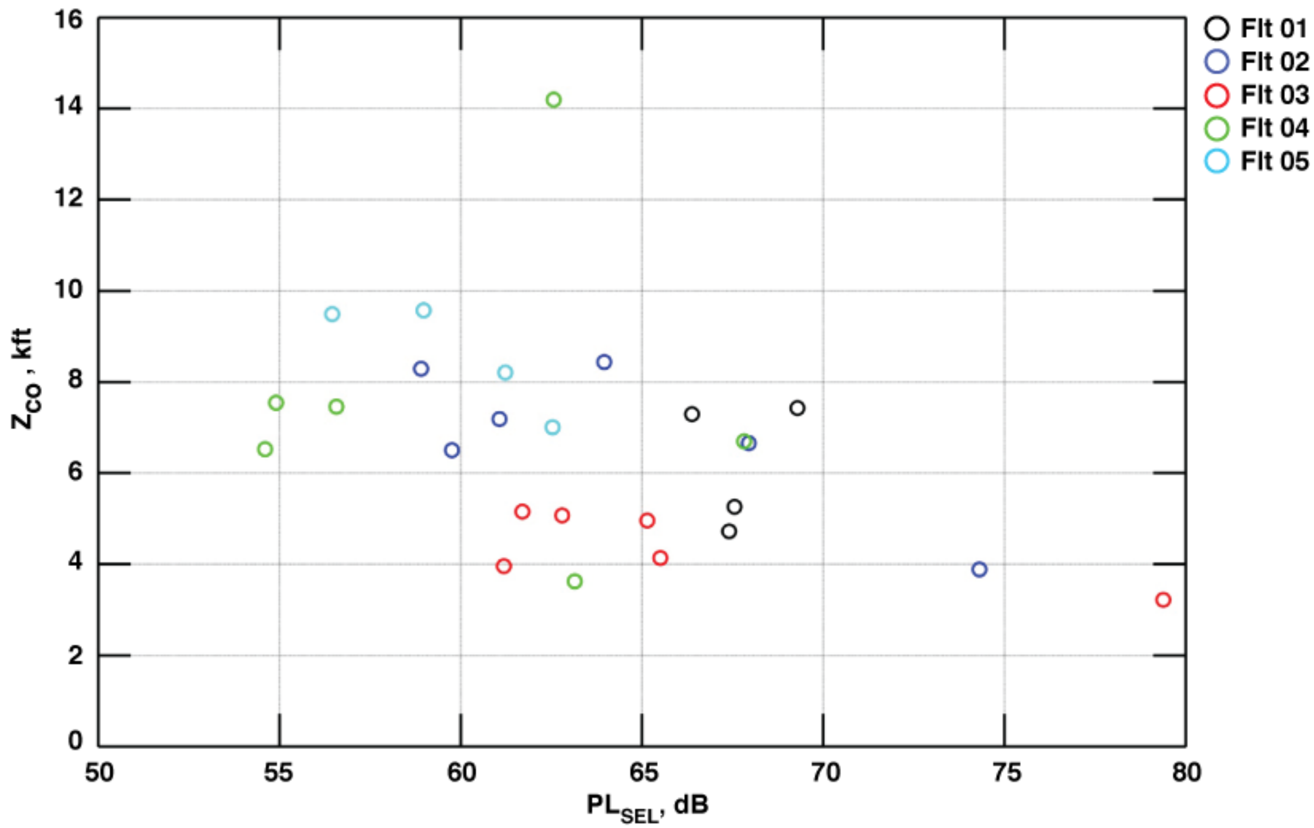
Noise Levels Due to Mach Cutoff

- New parameter: $(M_T - M)$
  - Relates Z_{CO} to Mach number
  - More natural to commercial piloting operations
- However, correlation between $(M_T - M)$ and noise on the ground (PL_{SEL}) is indistinct due to varying Z_{CO}



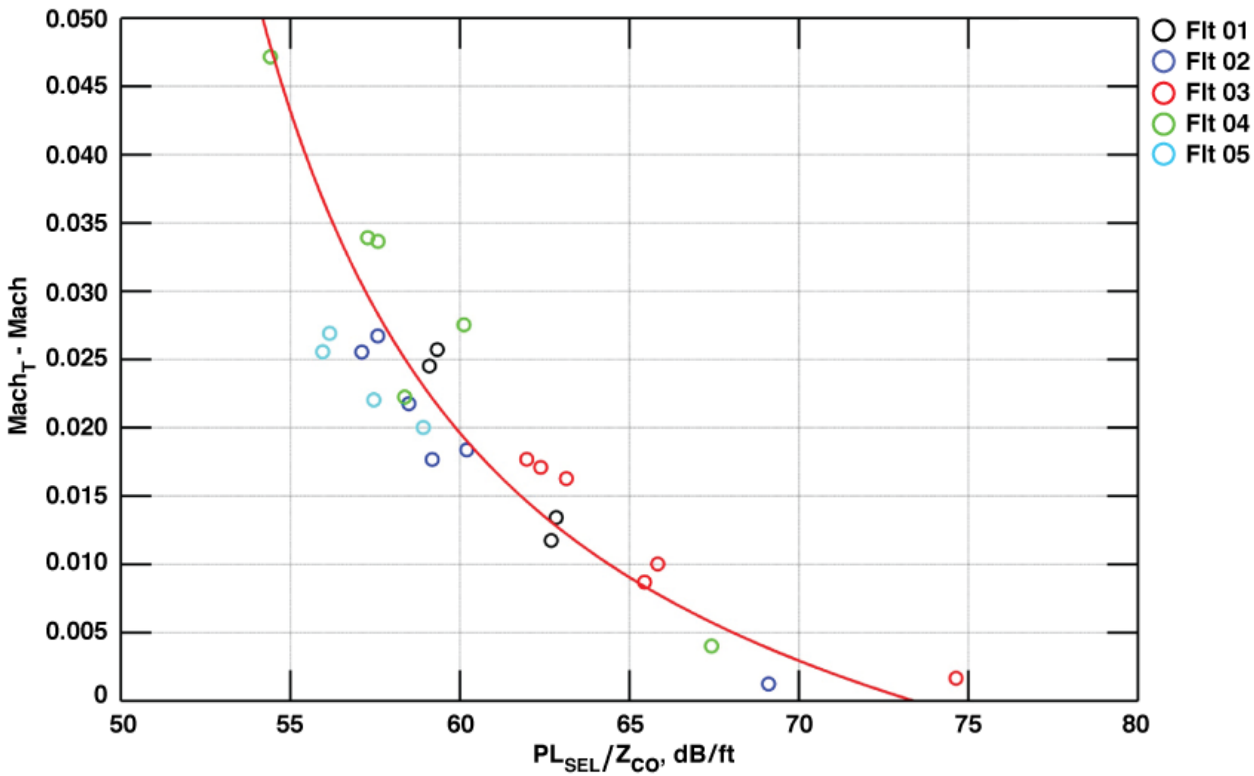
Noise Levels Due to Mach Cutoff, *cont.*

- Correlation between Z_{CO} and PL_{SEL} is also indistinct
- Possibly due to sonic boom shock strength (Mach number)



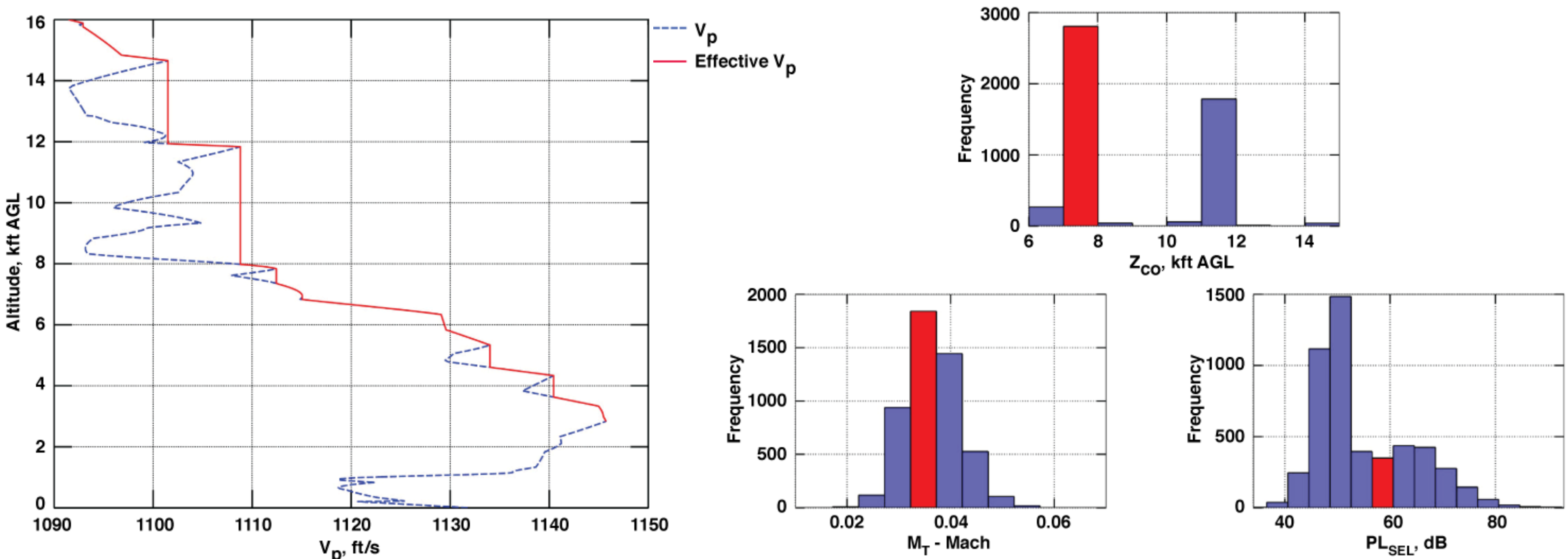
NOISE LEVELS DUE TO MACH CUTOFF, *CONT.*

- "Normalize" by Z_{CO}
- **First known empirical model for shadow zone acoustics:** $PL_{SEL} = f(M_T - M, Z_{CO})$
- Exponential decay fit ➔ evanescent wave field



SENSITIVITY ANALYSIS

- Monte Carlo simulation of 5000 M_{CO} cases
  - Constant Mach (1.135) and altitude 37000 ft *(11277.6 m)*
  - Random normal distribution of: wind speed (σ = 3 knots), wind direction (σ = 10 deg), and temperature (σ = 3 °C)
- "Banding" of Z_{CO} due to "effective V_P"



Red bars are as-flown values

Summary & Considerations

- PL_{SEL} shown to be a more consistent and applicable metric Mach cutoff sonic boom acoustics
- First known empirical model of Mach cutoff shadow zone acoustics allows:
  - The ability to predict sonic boom noise levels in real-time
  - Capability to design supersonic commercial airplane mission profiles for entire flight regime
  - Fast analysis. Computational models require significant computer core hours
- M_{CO} is extremely sensitive to atmospheric changes
  - Commercial applications will require sophisticated flight planning tools

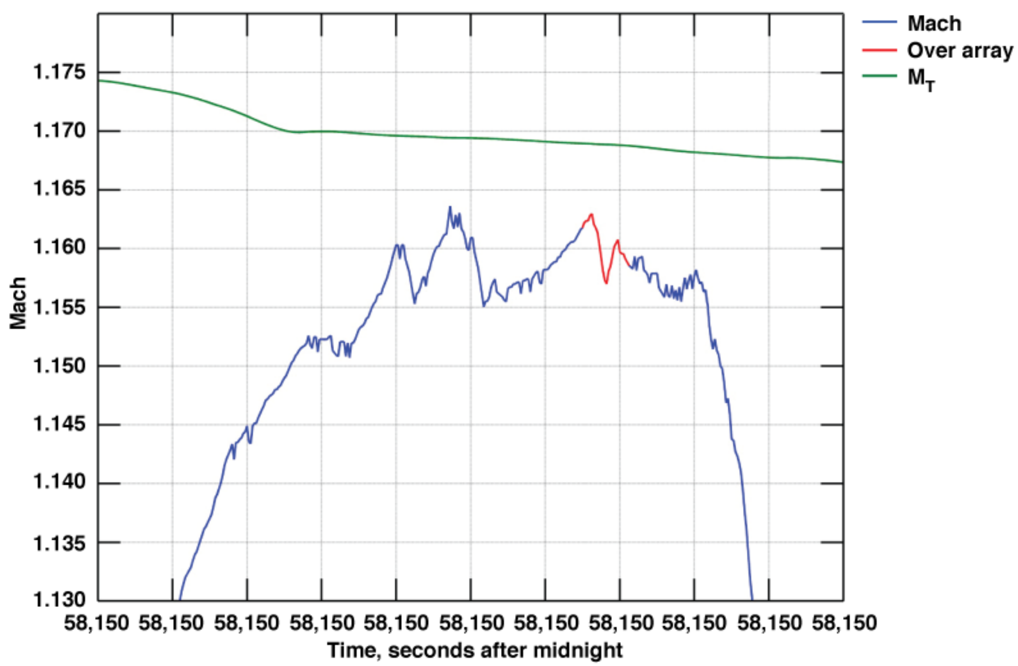
Future & Additional Work

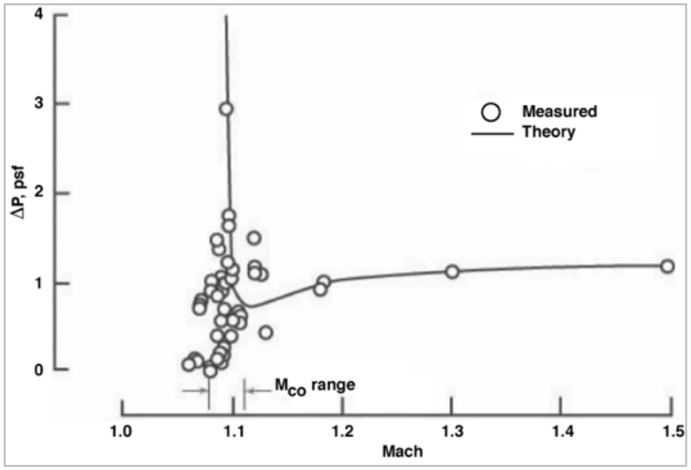
- Larger database to refine empirical model
- Verification of empirical model during flight
- Use model to validate computational codes, such as Gulfstream’s Lossy Nonlinear Tricomi Equation (LNTE)
- Beamforming analysis (Boeing)

THANK YOU.

Mach Cutoff Calculations, *cont.*

- Importance of accurate windowing





SENSITIVITY ANALYSIS, *CONT.*

- Changes in both atmosphere and flight parameters